

# Capacity Evaluation of a High Altitude Platform Diversity System Equipped with Compact MIMO Antennas

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**Abstract**— In this paper we address the potential gain of using compact MIMO antenna array configurations in conjunction with High Altitude Platforms (HAPs) diversity techniques in order to increase the capacity in HAP communication systems. For this purpose, we also propose a novel compact MIMO antenna which we denote as the “MIMO-Octahedron” and compare its performance with the vector element antenna. Simulation results show that the MIMO-Octahedron antenna provides superior performance to the vector element antenna and the single HAP case.

**Index Terms**—High Altitude Platforms (HAPs), compact MIMO antennas, diversity techniques, 4G systems

## I. INTRODUCTION

High Altitude Platforms (HAPs) are quasi-stationary aerial platforms operating in the stratosphere. This emerging technique is preserving many of the advantages of both satellite and terrestrial systems [1-5] and presently started to attract more attention in Europe through the European Community CAPANINA Project and the recently formed COST 297 Action, in which the authors are the Swedish representatives in this Cost Action. Recently, the first author has led an international editorial team for a HAP special issue at EURASIP Journal of Communications and Networking [1] to promote this technology and the research activities of Cost 297 to a wider audience. Cost 297 is the largest gathering of research community with interest in HAPs and related technologies [1].

Using narrow bandwidth repeaters on HAP for high speed data traffic have several advantages compared to using satellites, especially when operating in a local geographical area. One of the main advantages is that the received signal from the HAP would be much stronger than a received signal of equal transmitted power from a satellite. This allows for a much lower sufficient transmitter power which would decrease the size and weight of the repeater equipment carried by the HAP. Also the HAP provides for a much easier deployment so that a high-speed connection can be made on demand for a specific geographical area [1].

It has been widely recognized that the capacity in wireless communication systems can be greatly increased by exploiting environments with rich scattering such as urban areas or indoors [6-9]. Independent spatial or polarization channels can be accessed by means of multiple antennas at both the transmitter and the receiver and the technique is thus referred to as Multiple-Input Multiple-Output (MIMO) system. For a fixed total power and bandwidth, and with a matrix transfer function of independent complex Gaussian random variables, the MIMO wireless communication channel has an information theoretic capacity that (initially) grows linearly with the number of antenna elements [6-9].

Constellations of multiple HAPs have been shown to enhance broadband fixed wireless access capacity by exploiting antenna user directionality, when using shared spectrum in co-located coverage areas, where a predominant LOS propagation is present for mm-wavebands (e.g., 47/48 GHz). In addition, HAPs have been also proposed for 3G and broadband applications where multipath propagation might be significant. The central idea in this paper is to create a virtual MIMO system by exploiting the diversity provided by multiple HAPs (see figure 1) in order to increase the capacity in HAP communication links. In addition, a number of different compact antenna array configurations, (e.g., the vector element antenna and our proposed novel MIMO-Octahedron antenna) specifically designed for MIMO applications, in which the propagation environment is further utilized to achieve diversity in space and polarization. Thus, in this paper we also analyse the effect of using these different compact MIMO antenna configurations and power control on the information theoretic capacity of the total transmission channel of the HAP system.

The organization of the remainder of the paper will be as follows. In Section 2, we give a theoretical background of the polarization and pattern of antennas. The MIMO-HAP diversity system and various used MIMO antennas are presented in Section 3. The basic of MIMO-OFDM system and power control are presented in Section 4. In Section 5, the simulations results of the different MIMO antenna array configurations and presented. Finally, Section 6 concludes the paper.

## II. THE POLARIZATION CHANNEL

The polarization and antenna pattern of the electromagnetic field can be expressed as a multipole expansion [10] of the field emanating from a virtual sphere enveloping the antenna that is being analyzed. This series expansion consist of weighted orthogonal base functions on the surface of the virtual sphere and allow for a solution to Maxwell's equations that can be written as:

$$\begin{cases} \mathbf{E} = \sum_{l,m} \left[ \frac{j}{k} a_E(l,m) (\nabla \times f_l(kr)) \mathbf{X}_{lm} + a_M(l,m) g_l(kr) \mathbf{X}_{lm} \right] \\ \mathbf{H} = \frac{1}{\eta} \sum_{l,m} \left[ a_E(l,m) f_l(kr) \mathbf{X}_{lm} - \frac{j}{k} a_M(l,m) (\nabla \times g_l(kr)) \mathbf{X}_{lm} \right] \end{cases} \quad (1)$$

These base functions  $\mathbf{X}_{lm}$  are orthogonal functions of the spherical field when the far-field of the antenna is projected onto the virtual sphere. The functions  $g_l$  and  $f_l$  in equation (1) are Hankel functions representing an outgoing (transmitted) wave or an incoming (received) wave. The weights  $a_E$  and  $a_M$  are the corresponding coefficients and will give the gain of each orthogonal function (mode) for a particular electromagnetic far-field pattern, as shown by equation (2):

$$\begin{cases} a_E(l,m) \cong \frac{\mu_0 c k^2}{j \sqrt{l(l+1)}} \int Y_{lm}^* \left[ c \rho \frac{d}{dr} \left[ \frac{r}{j_l(kr)} \right] + j k (\mathbf{r} \cdot \mathbf{J}) j_l(kr) - j k \nabla \cdot (\mathbf{r} \times \mathbf{M}) j_l(kr) \right] d^3 \mathbf{r} \\ a_M(l,m) \cong \frac{\mu_0 c k^2}{j \sqrt{l(l+1)}} \int Y_{lm}^* \left[ \nabla \cdot (\mathbf{r} \times \mathbf{J}) j_l(kr) + \nabla \cdot \mathbf{M} \frac{d}{dr} \left[ \frac{r}{j_l(kr)} \right] + k^2 (\mathbf{r} \cdot \mathbf{M}) j_l(kr) \right] d^3 \mathbf{r} \end{cases} \quad (2)$$

Using equation (2) we can calculate which modes are active on any arbitrary antenna enveloped by a virtual sphere only by knowing the current distribution  $\mathbf{J}$ , the charge distribution  $\rho$  and the intrinsic magnetization  $\mathbf{M}$  of the antenna. These modes are theoretically orthogonal to each other and therefore represent independent ports of the antenna. The transmitting channel  $\mathbf{H}_{tx}$  is then assumed as the linear transformation of the input signal  $\mathbf{x}$  into the mode domain  $\mathbf{a}_{tx}$  according to  $\mathbf{a}_{tx} = \mathbf{H}_{tx} \mathbf{x}$  and for the receiving channel we have a similar transformation from the mode domain  $\mathbf{a}_{rx}$  into the output signal  $\mathbf{y}$  of the system following  $\mathbf{y} = \mathbf{H}_{rx} \mathbf{a}_{rx}$ , where  $\mathbf{a}_{tx}$  and  $\mathbf{a}_{rx}$  are vectors containing the mode gains for a specific antenna type.

## III. THE MIMO-HAP DIVERSITY SYSTEM MODEL

In this paper we are propose an application for high data rate transmissions using a system employing multiple HAPs. This system consists of virtually created MIMO channels using HAP diversity in combination with the polarization and pattern diversity of a special type of MIMO antenna arrangements [11-13] and also through using the OFDM modulation technique. Note

that the OFDM format is useful for propagation scenarios in 3G frequency band and is a promising candidate for many 4G communication systems. Figure 1 shows the diversity setup for the case of three HAPs separated by the angles  $\theta_{a,b}$  and  $\theta_{a,c}$ .

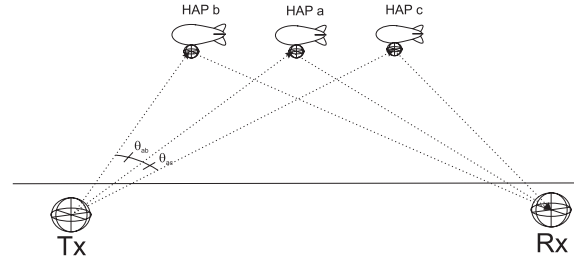


Figure 1: The MIMO-HAP diversity system with three HAPs and the channel paths from the transmitter to the receiver.

Each transmit and receive antenna of the system consists of a special compact MIMO antenna array. These compact antenna arrays can be of different complexity and design. In Fig. 2a we show the structure of a vector element antenna consisting of three orthogonal electric dipoles forming an electric tripole together with a magnetic tripole formed by three orthogonal magnetic dipoles (loop antennas) which will give a maximum of six independent antenna ports.

The second compact antenna we propose and investigate is a novel array configuration, which we denote as the "MIMO-Octahedron". This antenna consists of twelve electric dipoles positioned in double tetrahedron geometry, as can be seen in Fig. 2b. This design is created by taking two MIMO-Tetrahedron arrays and placing them with one tetrahedron vertex facing a vertex of the other tetrahedron, and then rotating one of the tetrahedrons 60 degrees around the axis going through both vertices and finally displace one of the tetrahedron so that they both have the same central point. Theoretically this will give twelve independent ports.

The three electric and three magnetic tripoles on their own do not provide enough independent antenna ports to be able to utilize the HAP diversity feature which would require at least four independent channels. Thus, the comparison of the capacity is done for the vector element antenna and the MIMO-Octahedron antenna only.

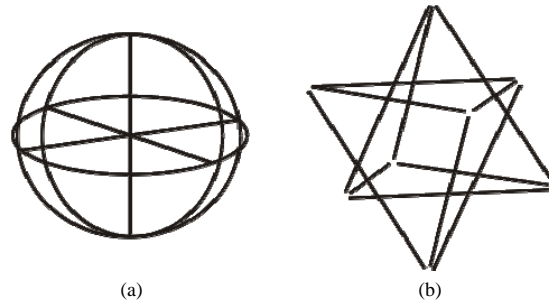


Figure 2: The structure of the two compact MIMO antennas: (a) The Vector element antenna, and (b) the MIMO-Octahedron antenna.

The wave propagation channel  $\mathbf{H}_{ch}$  from the transmitter mode vector  $\mathbf{a}_{tx}$  to the receiver mode vector  $\mathbf{a}_{rx}$  can be seen as a simple transformation that contain the distance dependent decaying values of the signal being transmitted

$$H_{mn}(\mathbf{r}, f) = \left( \frac{f}{4\pi c |\mathbf{r}_m - \mathbf{r}_n|} \right)^2 \quad (3)$$

where  $|\mathbf{r}_m - \mathbf{r}_n|$  is the distance along the path between transmitter m and receiver n. There are no atmospheric interferences and the noise in the system is modelled as uncorrelated Gaussian noise. The total MIMO channel can then be assembled as:

$$\mathbf{H} = \mathbf{H}_{rx} \cdot \mathbf{H}_{ch} \cdot \mathbf{H}_{tx} \quad (4)$$

where  $\mathbf{H}_{tx}$  and  $\mathbf{H}_{rx}$  are the transmitter and receiver antenna channels respectively.

#### IV. THE MIMO-OFDM SYSTEM MODEL

Assuming that we have a MIMO antenna system with N transmitting antennas and M receiving antennas, we can then write the separate signals in the frequency domain between any pair of transmitting and receiving antennas as:

$$\mathbf{r}(k) = \mathbf{H}(k)\mathbf{s}(k) + \mathbf{v}(k) \quad (5)$$

where  $\mathbf{r}(k)$  and  $\mathbf{s}(k)$  denotes the received and transmitted signals and  $\mathbf{H}(k)$  is the frequency response of the channel between N transmitters and M receivers. The noise in the system  $\mathbf{v}(k)$  is assumed to be uncorrelated Gaussian noise.

By using singular value decomposition (SVD) technique we can now write the channel matrix  $\mathbf{H}(k)$  as:

$$\mathbf{H}(k) = \mathbf{U}(k)\mathbf{\Sigma}(k)\mathbf{V}^H(k) \quad (6)$$

where  $\mathbf{\Sigma}(k)$  is an  $N \times M$  matrix containing the singular values that are larger than zero  $\sigma_1(k) \geq \sigma_2(k) \geq \dots \geq \sigma_r(k) > 0$ , where  $\mathbf{U}(k)$  and  $\mathbf{V}(k)$  are matrices with the corresponding vectors as columns. To obtain a diagonalized system we define:

$$\mathbf{y}(k) = \mathbf{\Sigma}(k)\mathbf{x}(k) + \mathbf{n}(k) \quad (7)$$

with

$$\begin{aligned} \mathbf{y}(k) &= \mathbf{U}^H(k)\mathbf{r}(k) \\ \mathbf{s}(k) &= \mathbf{V}(k)\mathbf{x}(k) \\ \mathbf{n}(k) &= \mathbf{U}^H(k)\mathbf{v}(k) \end{aligned} \quad (8)$$

Since the channels in equation (6) are uncorrelated and the correlation matrix of the noise  $\mathbf{n}(k)$  is  $\sigma_n^2 \cdot \mathbf{I}$  then we can write the theoretical information capacity [6-8] as:

$$C = \sum_{k=0}^{N_{FFT}-1} \sum_{m=1}^r \log_2 \left( 1 + \sigma_{x_m}^2(k) \frac{\sigma_m^2(k)}{\sigma_n^2} \right) \quad (9)$$

where  $\sigma_{x_m}^2(k)$  is the variance of the separate uncorrelated input signals in  $\mathbf{x}(k)$ . The capacity in equation (9) is constrained by the total radiated power from the transmitting antennas, defined as:

$$P = \sum_{k=0}^{N_{FFT}-1} \sum_{m=1}^r \sigma_{x_m}^2(k) \quad (10)$$

To maximize the total sum of capacities in all the sub-channels we use the so called “water-filling” technique in which we allocate more power to the sub-channels with high eigenvalues. The optimal “water-filling” solution [9] is then given by:

$$\begin{cases} s_{x_m}^2(k) = \gamma - \frac{s_n^2}{s_m^2(k)}, & \text{if } \gamma - \frac{s_n^2}{s_m^2(k)} > 0 \\ s_{x_m}^2(k) = 0, & \text{if } \gamma - \frac{s_n^2}{s_m^2(k)} \leq 0 \end{cases} \quad (11)$$

where  $\gamma$  is a pre-defined threshold level of the signal-to-noise ratio in the system.

#### V. SIMULATION RESULTS

In this section we compare the achieved capacity using different types of compact MIMO antenna configurations. The type of antennas used here are the vector element antenna and our proposed novel MIMO-Octahedron antenna. In these simulations we use a diversity system consisting of three or six HAPs, depending on whether we use the Vector element antenna or the MIMO-Octahedron antenna. These results were obtained for a system of HAPs operating at an altitude of 20 km and with a separation angle of 30 degrees, as shown in Fig. 1.

The capacity achieved by the compact MIMO antennas can be seen from Fig. 3 where the capacity is plotted against the average signal-to-noise ratio of the system. It is evident from this figure that the MIMO-HAP diversity system provides superior performance as compared to the single HAP or SISO (single-input single-output) case, and the MIMO-Octahedron antenna provides a better capacity than the vector element antenna due to the higher number of acquired independent channels. It is worth to mention that the electric and magnetic tripoles on their own did not provide enough channels to make the HAP diversity work.

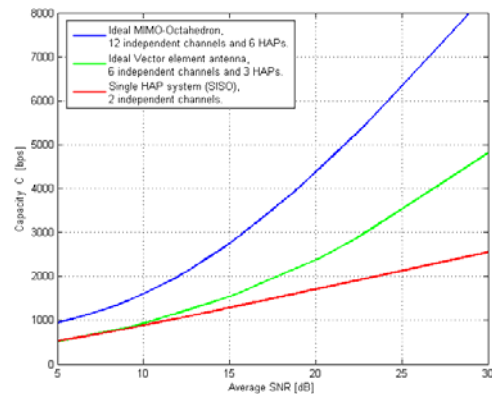


Figure 3: The capacity versus the average SNR for a separation angle of 30 degrees between HAPs.

## VI. CONCLUSIONS

In this paper we have studied the potential gain of using compact MIMO antennas and HAP diversity techniques in order to increase the capacity in HAP communication systems. Our results have shown that the combined MIMO-HAP diversity system provide significant capacity enhancement compared to the single HAP (SISO) system. Simulation results also show the performance of our proposed novel compact MIMO-Octahedron antenna array is superior to the Vector element antenna due to the higher number of acquired independent channels. Using the vector element antenna will give six independent channels and has also the disadvantage that we have to feed both electric and magnetic dipoles which makes for a more complicated interface to the antenna.

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